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Urbanization, sedimentation, and the homogenization of fish assemblages in the Etowah River Basin, USA

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Abstract

We tested the hypothesis that urbanization alters stream sediment regimes and homogenizes fish assemblages in 30 sub-basins of the Etowah River. Sediment variables included average particle size (mean *phi*) of the stream bed, percent fines (<2 mm) in riffles, and baseflow turbidity (NTU). Homogenization was quantified as ratios of endemic to cosmopolitan species richness (E_r:C_r) and abundance (E_a:C_a). High NTU and fine stream beds were associated with homogenized assemblages (i.e., lower E:C ratios). Mean *phi* and NTU were significantly correlated with E:C ratios ($r = -0.74$ to -0.76) and, when combined using multiple regression, accounted for 73% of the variance in ratios. Stream slope strongly covaried with mean *phi* ($r = -0.92$) and percent fines in riffles ($r = -0.79$), but multiple regression models showed that urbanized sites had finer beds and riffles than predicted by slope alone. Urban land cover was the primary predictor of NTU ($r^2 = 0.42$) and, combined with slope in multiple regression, explained 51% of the variance in NTU. Our results indicate that stream slope is a background variable predicting particle size and E:C ratios in these streams. Urbanization disrupts these relationships by transforming clear streams with coarse beds into turbid streams with finer beds. These conditions favor cosmopolitan species, ultimately homogenizing fish assemblages. Bed texture was linked to urbanization; however, NTU was the best indicator of urban impacts because it was statistically independent from slope.

Introduction

Urban development is a pervasive form of environmental disturbance that globally threatens stream systems. Urbanization causes major changes in stream hydrology, geomorphology, water quality, and stream communities (Baer & Pringle, 2000). Degradation of stream ecosystems occurs at low levels of urban land cover, and a growing body of evidence suggests that the impact of urbanization is more severe than other land uses such as agriculture or forestry (Paul & Meyer, 2001). Urbanization has been associated with declines in fish richness, diversity, density, and biotic integrity (Paul & Meyer, 2001), but its role in homogenizing fish assemblages is unstudied.

Homogenization generally refers to the replacement of regionally distinct faunas with a few invasive species tolerant of human disturbance (McKinney & Lockwood, 1999). These invasive species are usually characterized as widespread, generalist, cosmopolitan or ‘weedy’ species that gain access to degraded habitats either through range expansion or human introduction. They replace narrowly distributed, often specialized, endemic taxa that are sensitive to habitat alteration (McKinney & Lockwood, 1999). This process is well documented for terrestrial systems and organisms such as birds and plants (McKinney & Lockwood, 1999), but is relatively understudied for aquatic systems and fishes. Recently, Rahel (2000) found that extensive homogenization of fishes in the conterminous United States was due largely to introductions of fishes for angling and aquaculture. Scott & Helfman (2001) attributed homogenization of assemblages in Southern Appalachian streams to range expansion of native cosmopolitans and riparian disturbance, and they hypothesized that differential tolerance of endemic and cosmopolitan species to excessive sedimentation contributed to the process.

In this study, we quantified relationships between urbanization and homogenization in the Etowah River basin, a system with exceptional levels of fish endemism and a long history of land disturbing activities (e.g., mining and agriculture) (Burkhead et al., 1997). In an earlier study of these streams, Walters (2002) found that endemics were benthic specialists positively associated with steep gradients and coarse stream beds, but that endemics declined with increasing urban land cover. The mechanism of decline was not identified, but altered sediment regime was implicated. Urbanization substantially increases stream sediment inputs through upland erosion or increased bank scour (Wolman, 1967), and we predict that changes in sediment regime contribute to the decline of endemics fishes. We predict that cosmopolitans will increase because they are adapted to lowland river systems that often have higher turbidities and finer stream beds than upland streams and that, as upland streams become more sediment-laden, they become more hospitable to cosmopolitan species. Specifically, we address the questions: (1) Do ratios of endemic to cosmopolitan fishes decline with increasing turbidity and finer stream beds; and (2) Are increasing turbidity and finer stream beds associated with urbanization in a basin with a history of soil disturbing activities?

Materials and methods

We sampled 30 Piedmont streams draining basins of 11–126 km^2 in the Etowah River basin immediately north of Atlanta in northern Georgia, U.S.A. Large-scale human disturbance of the region began around 1830 and included gold mining, deforestation, and row crop agriculture (Burkhead et al., 1997). Much of the area was reforested after around 1930. Extensive urbanization of the area began around 1980 and the Atlanta metropolitan area is currently one of the most rapidly developing regions in the United States (U.S. Department of Agriculture, 2000). The Etowah drains part of the Southern Appalachian Highlands, a region widely recognized as a global hotspot of temperate freshwater fish diversity and endemism (Warren et al., 2000). The Etowah has 91 native fishes in 18 families including 11 species endemic to the larger Alabama River drainage, which includes the Etowah basin (Burkhead et al., 1997).

Fishes were sampled in summer 1999 and 2000 by electrofishing reaches 40 times stream width. Sampled reaches ranged in length from 200 to 400 m, and detailed sampling methodology is available in Walters (2002). Homogenization was calculated as the ratios of endemic to cosmopolitan species richness (E_r:C_r) and abundance (E_a:C_a). Low values indicate dominance by cosmopolitan species and a high degree of homogenization. We defined cosmopolitan species as fishes native to at least 10 major drainages (Warren et al., 2000) and endemics as species whose distributions are limited primarily to the highland region of the Alabama River drainage (Mettee et al., 1996) (Appendix 1).

Stream slope and bed sediment variables were measured in reaches scaled to 20 times average baseflow stream width. Slope was calculated as the average gradient of the water surface between the tops of riffles and was surveyed with an electronic total station (TOPCON® GTS-311). Mean *phi* of the stream bed was determined from visual counts conducted systematically along 5 longitudinal transects within the wetted channel (Walters, 2002). Mean percentage of fines in riffles (particles $<$2 mm by sieved weight) was calculated from three-liter soil samples taken from the top 10 cm of three riffles in each reach. Geometric mean turbidity (nephelometric turbidity units, NTU) was calculated from six baseflow samples collected throughout the year. To ensure comparable baseflow conditions, we limited sampling to periods without significant rainfall during the previous 72 h.

Land cover data were derived from Landsat TM images from June 1987 and July 1997 (Lo & Yang, 2000). Two urban land cover types were classified. High-density urban (HDU) was 80–100% construction material and included commercial developments and multi-lane highways. Low-density urban (LDU) is 50–80% construction material and is characterized by single or multiple family housing developments and smaller roads. The percentage of LDU and HDU were summed to calculate total basin urban land cover (U). Totals from 1987 were subtracted from 1997 totals to calculate the percentage of basin area converted to each urban category. These urban conversion variables indicated the intensity of urbanization for each basin over the decade.

We used Pearson correlation analysis to assess the relationship of homogenization to sediment and urban variables. Appropriate transformations were applied to achieve normality of independent and dependent variables prior to statistical analysis. Stream slope and basin area were included in these analyses because they were predictive of some elements of fish assemblage structure and because slope covaried with some bed texture variables (Walters, 2002). We used forward stepwise regression to develop three sets of models linking the fishes and independent variables. First, we developed models of sediment and E:C ratios. Second, we modeled sediment variables using stream size, slope, and urban land cover. Finally, we modeled E:C ratios combining urban, geomorphic, and sediment variables. The latter hierarchical models assessed the relative predictive power of variables measured at basin, reach, and microhabitat (i.e., fines in riffles) scales to explain variation in E:C ratios.

Results

Species richness ranged from 10 to 30 species across sites with a range of 0 to 38% endemic species and 0 to 65% endemic abundances. Cyprinids, centrarchids, and percids were the most common fishes and frequently accounted for >70% of site species richness and abundance. Reach slope varied from 0.001 to 0.01, mean *phi* ranged from −6.4 (cobble) to 0.4 (sand), and baseflow turbidity varied from 2.7 to 17.8 NTU. Urban land cover (U) varied from 5 to 37% and mean U across sites nearly doubled from 8 to 15% from 1987 to 1997. Low-density urban (LDU) was the dominant type of development and accounted for about 87% of total U.

The E:C ratios were highly autocorrelated (r = 0.94) and showed a similar response to sediment and urban variables (Table 1). Homogenization ratios were negatively correlated with NTU, fines in riffles, and mean *phi* indicating that endemic species decline and cosmopolitan species increase in turbid streams with fine-textured beds. The E:C ratios increased with stream slope and were negatively correlated with urban land cover. Urban land cover was a poor predictor of bed texture, but was positively correlated with baseflow NTU. In contrast, stream slope was a strong predictor of both bed texture variables and was negatively correlated with NTU.

Mean *phi* and baseflow NTU explained nearly 75% of the variance in E:C ratios (Table 2). In the *phi* scale, smaller particles have larger values, so the negative correlations indicated that E:C ratios increased as the size of bed sediment increased. Much of the variation in local bed texture and NTU was explained by a combination of reach slope and urban land cover. Slope was the primary predictor of mean *phi*, but urban land cover was associated with finer stream beds and riffles than predicted by slope alone. Finer stream beds were associated with LDU development from 1987 to 1997, and fines in riffles increased significantly with HDU. Urban land cover was the primary predictor of NTU, but lower baseflow NTU was also associated with steeper streams.

We could not include both mean *phi* and slope in the stepwise procedure because they covaried too strongly. Compared with bed sediment, slope is essentially invariant to changes in catchment land use in the context of our study. Thus, we treated slope as a background variable controlling bed texture and used it for the stepwise analysis. Even though NTU and 1997 U were also related, correlation strength (r = 0.65) was low enough to include both variables in the analysis. The stepwise procedure indicated that baseflow NTU was the strongest predictor of homogenization ratios followed by slope, and 1997 U. Hierarchical models explained 81% and 77% of the variance in E_r:C_r and E_a:C_a, respectively. Percent 1997 U entered into the models along with NTU suggesting that additional urban influences (other than elevated turbidity) contribute to homogenization of the fish assemblages.

Discussion

Our results agree with the general hypothesis that large-scale human disturbance homogenizes regional faunas (McKinney & Lockwood, 1999). Urbanization alters stream habitats making them more favorable for cosmopolitan species. Reach-level variation in stream slope controlled bed texture, which is the primary predictor of E:C ratios. We used multiple linear regression to account for the nonanthropogenic influence of slope and to isolate the urban effect. This analysis indicated that urban development disrupted the relationships between fishes, bed sediment, and slope in at least two ways. Urbanization was associated with smaller bed-particle sizes and increased baseflow NTU. Thus, urbanization tended to transform clear streams with coarse beds into turbid streams with finer beds, favoring cosmopolitan species over endemic taxa.

Baseflow NTU was a better indicator of urban effects on fishes than measures of bed sediment. Although urban land cover explained significant variance in bed texture, the changes were subtle compared to the overriding influence of stream slope. Prior to intense human disturbance, the study area was forested

Table 1. Correlation matrix of ratios of endemic to cosmopolitan richness (E_r:C_r) and abundance (E_a:C_a), stream sediment variables, basin area and reach slope, and basin urban land cover (n = 30 sites). All correlations are Pearson's r. Land cover abbreviations: U = Urban; HDU = High Density Urban; LDU = Low Density Urban. Correlations significant at $p < 0.05$ are in bold; $p < 0.01$ are in bold and italics; $p < 0.001$ are in bold, italics, and underlined. Only 1997 urban variables are shown because the 1987 and 1987–1997 land cover variables showed similar trends

	E_r:C_r	E_a:C_a	NTU[1]	Mean *phi*	% fines[2]	Basin area (km^2)	Slope	1997% U	1997% HDU	1997% LDU
E_r:C_r	1									
E_a:C_a	***0.94***	1								
NTU[1]	−***0.75***	−***0.74***	1							
Mean *phi*	−***0.75***	−***0.76***	***0.53***	1						
% fines[2]	−***0.69***	−***0.62***	**0.40**	***0.79***	1					
Basin area	−0.25	−0.17	−0.13	0.24	0.23	1				
Slope	***0.70***	***0.67***	−**0.40**	−***0.92***	−***0.79***	−**0.37**	1			
1997 U	−***0.62***	−***0.62***	***0.65***	0.34	0.31	−0.11	−0.17	1		
1997 HDU	−***0.48***	−**0.45**	−***0.62***	0.07	0.21	−0.22	0.04	***0.84***	1	
1997 LDU	−***0.63***	−***0.64***	***0.64***	**0.39**	0.32	−0.08	−0.20	***0.99***	***0.78***	1

[1]Geometric mean turbidity at baseflow.
[2]Percent fines <2 mm (by weight) in riffles.

and streams reportedly were clear during low flows (Burkhead et al., 1997). Thus, high baseflow NTU indicates a departure from the natural condition and may identify streams that suffer from chronic sediment disturbance. The sources of fines contributing to baseflow NTU were not identified. Likely sources include baseflow transport of fine bed material introduced during flood flows and persistent near-stream disturbances such as road and housing construction.

Our study reports correlations and thus does not isolate causal mechanisms driving the response of fishes to changes in bed and suspended sediment. However, differences in life history traits among the two fish groups provide some clues about why cosmopolitan species appear to thrive under these conditions. The endemic species are, for the most part, benthic habitat specialists that inhabit riffles and runs, spawn in coarse gravel, and are specialist feeders on benthic macroinvertebrates (Etnier & Starnes, 1993). Bed sedimentation can negatively affect these species by burying riffle habitat, reducing egg and fry survivorship, and lowering prey densities through habitat destruction or increased drift (Waters, 1997). Cosmopolitan species exhibit a number of traits that make them more resilient to bed sedimentation. For example, centrarchids and ictalurids spawn in nests constructed in fine sediments. Many cosmopolitans are habitat generalists that frequent pools and runs and have less dependence on riffle habitat. In addition, these species are often omnivores or trophic generalists that rely less on production of benthic macroinvertebrates.

Elevated baseflow turbidity may impact trophic pathways and spawning success of endemic species. Turbidity induces drift of invertebrates and depletes local populations (Waters, 1997). In addition, turbidity reduces the capture success and reactive distance of drift feeding fishes (Waters, 1997; Sweka & Hartman, 2001). Turbidity can affect spawning behavior by disrupting spawning cues or curtailing spawning activity for species that exhibit striking nuptual coloration (Seehausen et al., 1997; Burkhead & Jelks, 2001), a common trait among Etowah endemics. Burkhead & Jelks (2001) showed that suspended sediment delayed spawning and reduced egg laying in *Cyprinella trichroistia*, one of the endemics in our study. Their experiment mimicked turbidities associated with high stream flows (e.g., a spike in suspended sediment concentration followed by a gradual attenuation as fines settled out of suspension). Our results were based on *baseflow* turbidity. High baseflow NTU indicates chronic turbidity problems that could inhibit spawning activity of some fishes indefinitely.

Conclusion

Homogenization is a serious threat to global biodiversity (McKinney & Lockwood, 1999; Rahel, 2000). Our study documented the homogenization of an en-

Table 2. Multiple linear regression models (using forward stepwise procedure) of endemic to cosmopolitan richness and abundance (E_r:C_r and E_a:C_a) and sediment variables. Land cover abbreviations are for low-density urban (LDU), high-density urban (HDU), and total urban (U). The *F* value shown is for the entire model

Independent variable	Variables in model	Trend	Cumulative r^2	*p*	*F*
	Sediment models of homogenization				
E_r:C_r	Mean *phi*	–	0.57	<0.001	
	NTU	–	0.74	<0.001	38.84
E_a:C_a	Mean *phi*	–	0.58	<0.001	
	NTU	–	0.73	<0.001	37.88
	Slope and land cover models of sediment variables				
Mean *phi*	Slope	–	0.84	<0.001	
	1987–97 LDU	+	0.90	<0.001	120.10
% fines	Slope	–	0.62	<0.001	
	1997 HDU	+	0.68	0.04	28.37
NTU	1997 U	+	0.42	<0.001	
	Slope	-	0.51	0.04	14.00
	Hierarchical models of homogenization				
E_r:C_r	NTU	–	0.57	<0.001	
	Slope	+	0.76	<0.001	
	1997 U	+	0.81	0.01	37.00
E_a:C_a	NTU	–	0.54	<0.001	
	Slope	+	0.71	0.005	
	1997 U	–	0.77	0.01	28.81

demic, highland stream fish fauna, and our results indicated that homogenization was related to increased levels of sedimentation associated with urban development. Forestry and agriculture were historically the major forms of anthropogenic disturbance of landscapes worldwide; however, urbanization is on the rise (Baer & Pringle, 2000). Erosion from urban development is particularly acute (Wolman, 1967), and we detected the urban effect on sediment regime even though the Etowah basin had a prior history of large-scale mining and agricultural disturbance. Limiting sediment inputs to streams and developing effective tools for monitoring sediment pollution are two key steps in conserving endemic stream fauna. Baseflow NTU is simple and inexpensive to collect, and our results indicate that it is a promising indicator of chronic sedimentation in highland streams.

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Appendix 1. Endemic and cosmopolitan fishes collected in the Etowah River system. Value in parentheses is the number of southern U.S. drainages in which widespread species are native (Warren et al., 2000). Endemics have ranges that are primarily limited to highlands in the Alabama River basin

Family name / ***Scientific name***	**Common name**	**Family name** / ***Scientific name***	**Common name**
Endemic Highland Species		Cosmopolitan Species (continued)	
Cyprinidae		**Ictaluridae**	
Cyprinella trichroistia	tricolor shiner	*Ameiurus brunneus*	snail bullhead (10)
Hybopsis lineapunctata	lined chub	*A. natalis*	yellow bullhead (40)
Notropis chrosomus	rainbow shiner	*A. nebulosus*	brown bullhead (30)
N. xaenocephalus	Coosa shiner	*Ictalurus punctatus*	channel catfish (40)
Phenacobius catostomus	riffle minnow	*Noturus leptacanthus*	speckled madtom (14)
Cottidae		**Poeciliidae**	
Cottus carolinae zopherus	Coosa banded sculpin	*Gambusia affinis*	western mosquitofish (24)
Percidae		*G. holbrooki*	eastern mosquitofish (15)
Etheostoma etowahae	Etowah darter	**Centrarchidae**	
E. jordani	greenbreast darter	*Ambloplites ariommus*	shadow bass (15)
E. scotti	Cherokee darter	*Lepomis auritus*	redbreast sunfish (16)
Percina palmaris	bronze darter	*L. cyanellus*	green sunfish (36)
P. sp. cf. P. macrocephala	'bridled darter'	*L. gulosus*	warmouth (47)
Cosmopolitan Species		*L. macrochirus*	bluegill sunfish (35)
Cyprinidae		*L. megalotis*	longear sunfish (37)
Campostoma oligolepis	largescale stoneroller (15)	*L. microlophus*	redear sunfish (35)
Notemigonus crysoleucas	golden shiner (51)	*Micropterus punctulatus*	spotted bass (30)
Notropis longirostris	longnose shiner (10)	*M. salmoides*	largemouth bass (47)
Pimephales vigilax	bullhead minnow (32)	*Pomoxis nigromaculatus*	black crappie (44)
Semotilus atromaculatus	creek chub (41)	**Percidae**	
Catostomidae		*Etheostoma stigmaeum*	speckled darter (17)
Minytrema melanops	spotted sucker (40)	*Percina nigrofasciata*	blackbanded darter (15)
Moxostoma duquesnei	black redhorse (21)		
M. erythrurum	golden redhorse (26)		
M. poecilurum	blacktail redhorse (12)		